Retrospective Analysis of Seismological Anomalies of *M*5.5 Earthquake Sequence in Pingyuan, Shandong

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Abstract. On August 6, 2023, an *M*5.5 earthquake occurred in Pingyuan County, Dezhou City, Shandong Province, which was the largest earthquake in North China since 2000. This earthquake broke the 626 days of *M*5.0 seismic quiescence in North China after the *M*5.0 earthquake in a sea area in Dafeng District, Jiangsu Province, on November 17, 2021. In this study, the geological structure of the epicenter was analyzed and the seismological anomalies in Shandong and adjacent areas before the earthquake occurred were sorted out.

Keywords: Pingyuan; Retrospective Analysis of Seismological Anomalies; Earthquake Sequence.

1 Introduction

As determined by the China Earthquake Networks Center, at 02: 33 on August 6, 2023, an *M*5.5 earthquake occurred in Pingyuan County, Dezhou City, Shandong Province (37.15°N, 116.33°E), with a focal depth of 10 kilometers and an epicentral intensity of VII. The epicenter of the Pingyuan *M*5.5 earthquake is located on the northwest side of the Guanxian–Lingxian Fault, and the long axis of the intensity map is northeast-trending. The focal mechanism solution is a strike-slip type.

The largest aftershock of the Pingyuan earthquake sequence was Pingyuan *M3.0* (*ML3.6*) on August 6. According to the difference between the main earthquake and the second largest earthquake magnitude and the energy ratio of the main earthquake and the aftershock, the Pingyuan *M5.5* earthquake sequence on August 6, 2023, was considered an isolated type[1].The M-t diagram of Pingyuan earthquake sequence is shown in Fig.1,the time interval diagram of aftershocks is shown in Fig.2.

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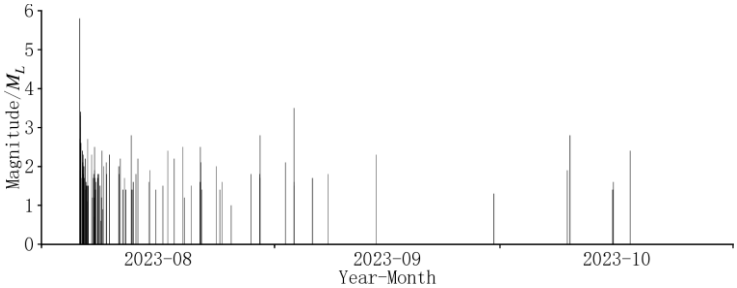

Fig. 1. The M-t diagram of Pingyuan *M*5.5 earthquake sequence

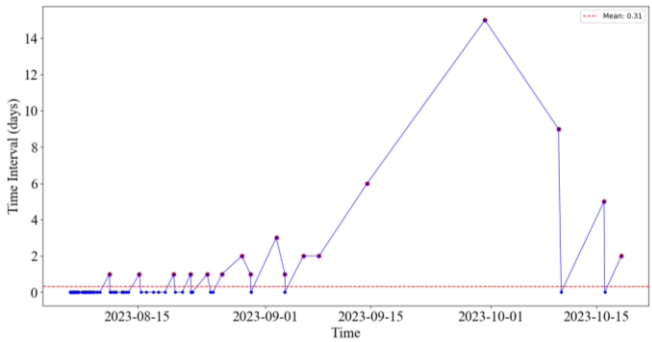

Fig. 2. Graph of ΔT -T of Pingyuan *M*5.5 earthquake sequence

2 Regional Geotectonic Background

The Pingyuan *M*5.5 Earthquake in Shandong occurred in the southwest of the Bohai Bay Basin, which is located in the northeast of North China Block—the largest craton in Eastern China. The most fundamental action came from the subduction and pushing of the Pacific Plate from east to west and the upwelling of molten materials in the deep mantle formed by subduction zones, which resulted in lithospheric thinning and the formation of Bohai Bay Basin. The Pacific Plate subducted and pushed from east to west, which was mainly reflected in the sinistral strike-slip movement of the NNE-trending Tanlu Fault Zone and the controlled sinistral strike-slip property of the NWW-trending Zhangjiakou–Bohai Fault Zone. Due to the upwelling of mantle materials, relatively perpendicular differential movements existed between active tectonic structures, e.g., the relatively perpendicular movement difference between Bohai Bay Basin and Luzhong uplift[2].

Pingyuan earthquakes presented a very concentrated special distribution, and the seismic activities mainly took place in a circular area with a radius of 20 km centered at 116.34°E and 37.16°N. Many faults (Fig.3) were distributed near the epicenter, among which the fault closest to the Pingyuan Earthquake was the Lingxian–Guanxian Fault, and the shortest distance from this fault line was about 1.9 km. Artificial seismic exploration results showed that the NW-trending Lingxian–Guanxian

Fault (F1) had a dip angle of about 70°, gradually becoming gentle from top to bottom, belonging to an early-middle Pleistocene fault. In the north was the nearly EW-trending Jiucheng Fault (F2), which inclined to the south direction with a dip angle of 60°. In the northeast was the NW-trending Huangheya Fault (F3), inclining in the SW direction, while its dip angle was unknown.

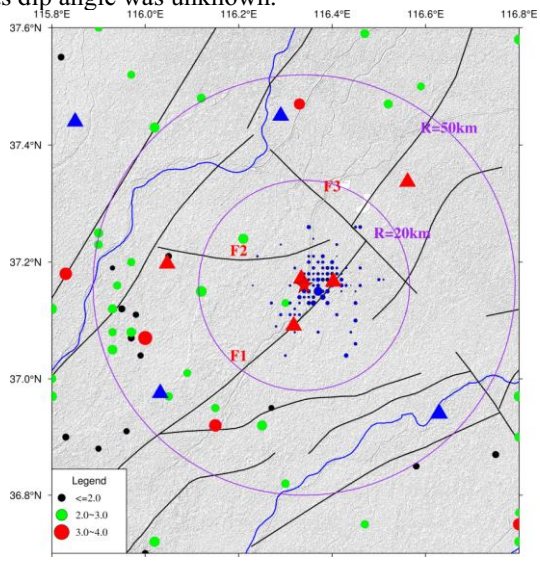

Fig. 3. Faults around Pingyuan 5.5 earthquake

3 Retrospective Analysis of Pre-earthquake Anomalies

3.1 Spatial-temporal clustering of *M*5.0 earthquakes in the east of North China

After the Zhangbei *M*6.2 earthquake in 1998, *M*6.0 seismic quiescence lasted 25 years in North China. Affected by Japan "3·11" *M*9.0 earthquake in 2011, concentrated moderately strong earthquakes took place in the east of North China within a short term in 2013, totaling five *M*5.0 earthquakes occurred, including the Liaoning Dengta *M*5.1 Earthquake on January 23, 2013, the Inner Mongolia Tongliao *M*5.3 Earthquake on April 22, and earthquakes in the south and north of the Yellow Sea. In recent years, moderately strong earthquakes have appeared again in North China, successively including the *M*5.1 Earthquake in Guye District in Hebei on July 12, 2020, the *M*5.0 Earthquake in a sea area of Dafeng District in Jiangsu on November 17, 2021, and the *M*5.0 Earthquake in Jeju Island of South Korea on December 14, 2021. This group of concentrated *M*5.0 seismic activities constituted one of the seismogenic backgrounds of the Pingyuan *M*5.5 Earthquake in Shandong[3].

3.2 Concentrated M_L4.0 moderate seismic activities in the middle of North China

After the Linzhang M_L4.2 Earthquake in Hebei Province on April 21, 2019, eight M_L4.0 or above earthquakes occurred in the middle of North China, especially in the central Shanxi Zone, through the Hebei Plain Zone to Jinan and Qingzhou in central Shandong Province, forming a concentrated area of moderate seismic activities and showing concentrated and enhanced seismic activities in the region before the Pingyuan *M*5.5 Earthquake[4].

3.3 M_L4.0 earthquake gap in the north of North China from 2020 to 2022

From 2020 to 2022, 11 M_L4.0 earthquakes in the north of North China formed an M_L4.0 earthquake gap. The maximum gap azimuth was <120°, the major axis of the gap was about 560 km, and the minor axis was about 320 km. The Pingyuan *M*5.5 Earthquake occurred on the edge of the gap. The major axis direction of this gap was NW-SE, which was the same as that of the Zhangjiakou–Bohai Fault Zone. On the northeast edge was the Zhangjiakou–Bohai Fault Zone, and on its southwest edge was the North China Plain Zone. This gap contained Beijing, Tianjin, Hebei, and Shandong, and the historical earthquake distribution in this gap showed that M_L4.0 earthquakes were relatively active. Therefore, this gap was worthy of tracking and attention[5].

3.4 M_L≥2.5 seismic belt from Cixian County to Renqiu County in Hebei

From January 24 to March 31, 2023, an M_L≥2.5 seismic belt was formed from Cixian County to Renqiu County in Hebei, which was 310 km in length and 75 km in width. As revealed by the analogy analysis of historical earthquakes, the estimation range of this M_L≥2.5 seismic belt covered the belt and its surrounding areas, the predicted earthquake magnitude was above M_L4.0, and the prediction period spanned within 200 days (October 21, 2023). The Pingyuan *M*5.5 Earthquake on August 6, 2023, was located in the time window for anomaly prediction in this belt[6-7].

3.5 Concentrated active M_L3.0 earthquakes in the north of North China

In the north of North China (36.0-43.0°N, 112.0-124.0°E), a total of 16 earthquakes with M_L≥3.0 occurred within half a year, spanning from April to October of 2022, which presented a concentrated active trend. The statistical results of the past earthquakes showed that a favorable prediction effect could be achieved for *M*>5.0 earthquakes in the north of North China.

3.6 Frequency of minor earthquake swarms in North China

In 2022, the Qingzhou earthquake swarm on May 2, the Haicheng earthquake swarm on May 17, the Penglai earthquake swarm on June 5, and the Gaizhou earthquake

swarm and the Hebei Cixian earthquake swarm on September 18 successively occurred consecutively in North China. In 2023, the Linzhou earthquake swarm in Hebei Province on March 25 and the Weishan earthquake swarm in Shandong Province on April 6 occurred one after another, reaching the index of seismological anomalies.

3.7 Precursory swarms

Before the Pingyuan *M*5.5 earthquake, earthquake swarms took place within a periphery range of 500 km multiple times, some of which were precursory[8-10].

Qingzhou earthquake swarm

The parameter calculation of the Qingzhou earthquake swarm sequence from May 1 to May 14, 2022, showed that the precursory swarm criteria like F, ρ, and h were satisfied, which was of certain indicative significance for moderately strong seismic activities within 500 km range of the main earthquake.

Penglai earthquake swarm

The Penglai earthquake swarm from June 5, 2022, to June 18, 2022, was precursory, as evidenced by the parameter calculation. Prediction efficiency was reflected as R=0.71, R_0=0.24, and R/R_0=2.97, indicating that M>5.0 earthquakes might occur within 500 km of the main earthquake in the year ahead. This prediction was valid until June 5, 2023.

Cixian earthquake swarm

An M_L3.2 earthquake occurred in Cixian County, Hebei, on August 11, 2022, and earthquake swarms were formed. According to the judgment criteria for the nature of M>1.0 earthquake swarms, this earthquake swarm was also precursory, as proved by such parameters as U, F, k, h, and b.

Weishan earthquake swarm

An M_L3.9 earthquake swarm activities had occurred in Weishan of Shandong since March 25, 2023. Based on the judgment criteria for the nature of M_L>1.0 earthquake swarms, the U, F, and h values manifested the precursory nature of this earthquake warm, which was of indictive significance for the moderate seismic activities in surrounding areas.

3.8 Activity anomalies in seismic windows

Before the Pingyuan *M*5.5 Earthquake, an “opening” anomaly occurred in the seismic window within this area[11-13].

Shandong Changdao seismic window

The Changdao seismic window was opened twice on December 14, 2020, and May 31, 2021, respectively, which means the daily and monthly frequency of M_L>1 earthquakes in the Changdao window exceeded eight times. Within a year, an *M*5.0 earthquake took place in a sea area in Dafeng District, Jiangsu, on November 17, 2021. On June 5, 2022, the Changdao window was opened continuously once again under the influence of Penglai earthquake swarms, indicating that *M*5.0 earthquakes might take place in the east of North China (29°-39°N, 114.5°-125°E) over the next year.

Hebei Xingtai seismic window

Since March 2023, dense minor seismic activities appeared in the old earthquake-stricken area of Xingtai, Hebei Province. Up to March 22, the strain energy of the Xingtai seismic window exceeded the threshold, reaching the windowing conditions, accompanied by significant spatial-temporal clustering characteristics of minor earthquake swarms. According to the retrospective analysis results of earthquake examples, the risks of M_L≥4.0, M_L≥4.5, and M_L≥5.0 earthquakes existed in the range of 100, 250, and 500 km within this window. In addition, the dominant occurrence time was six months. The Shandong Pingyuan *M*5.5 Earthquake occurred exactly in the windowing period of the Hebei Xingtai seismic window.

As shown above, seismological anomalies of *M*5.5 earthquake sequence in Pingyuan are shown in Fig.4.

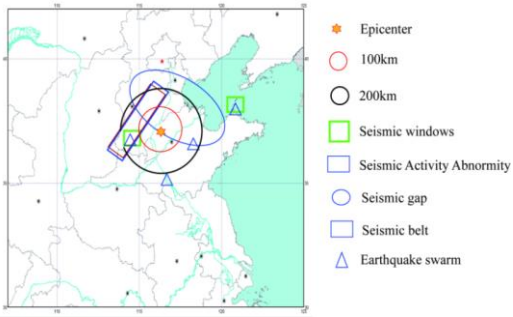

Fig. 4. Distribution of seismic activity abnomalities around *M*5.5 Pingyuan earthquake

4 Conclusion

Based on the retrospective analysis, three background anomalies were found in North China before the occurrence of the Pingyuan *M*5.5 Earthquake: long-term *M*6.0 seismic quiescence, concentrated *M*5.0 seismic activities, and concentrated and enhanced M_L4.0 moderate earthquakes. In addition, 11 background seismological anomalies were observed in Shandong and adjacent areas, including the broken 90-day M_L4.0 seismic quiescence in North China, an M_L4.0 earthquake gap formed in North China, the M_L≥2.5 seismic belt from Cixian County to Renqiu County in Hebei, the enhanced M_L3.0 seismic activities in the Pingyuan zone of Hebei, the frequency of earthquake

swarms, Qingzhou earthquake swarm, Penglai earthquake swarm, Cixian earthquake swarm, Weishan earthquake swarm, Changdao seismic window, and Xingtai seismic window. No short-term or imminent earthquake anomalies were identified.

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